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CESIUM VAPOR CATHODE STUDY

BY

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TECHNICAL NOTE NO. 3
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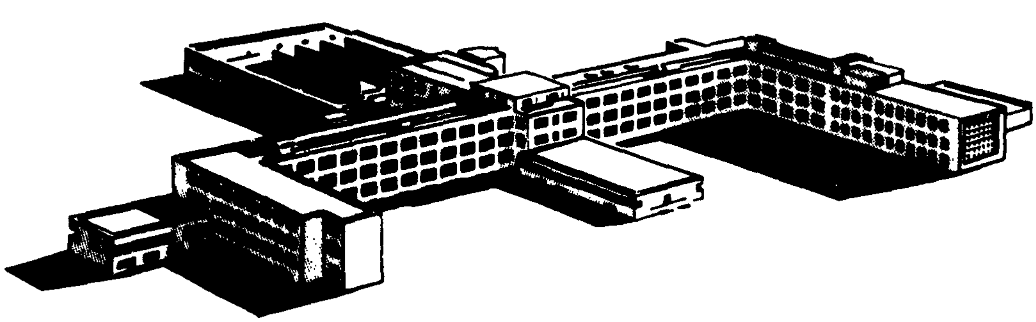

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ABSTRACT

Two approaches to the problem of extracting high-density electron beams from synthesized plasmas are under study: One uses a common surface for both ion and electron emission, the other employs separate surfaces.

The first tantalum common-emitter hollow cathode tube, designated CE-1, has been completed and awaits testing. The cathode, designed to yield an extracted current density of 100 amp/cm^2, has been taken up to its full operating temperature of 2250°K twice during tube processing with no mechanical or thermal difficulties being encountered.

Experiments were carried out on plasma-cathode tubes utilizing separate ion and electron emitters. These can be operated at temperatures lower than those of common-emitter surfaces since each emitter can be optimized separately. An extracted current density of 32 amp/cm^2 was obtained from the aperture in a niobium electrode (this electrode was used for contact ionization of cesium and was located opposite an L-cathode). However, the synthesized plasma in this tube turned out to be of the common-emitter type since L-cathode evaporants, which continually deposited on the niobium surface, caused the surface to be also a good electron emitter.

In another tube, a hafnium surface was used for cesium contact ionization and a duo-emitter-type plasma was successfully synthesized. The extracted current density through the aperture was 12.3 amp/cm^2. This density should be considerably increased if excess ions are provided in the exit aperture area and if greater precaution is taken to avoid contamination of the L-cathode.

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I. PLASMA GUNS UTILIZING SEPARATE ION AND ELECTRON EMITTERS

The results of tests performed on a plasma-cathode gun, which utilized an L-cathode for electron emission and an apertured graphite disk opposite it for ion emission, were reported in Technical Note No. 2.[1]

The maximum current density extracted was only 1.44 amp/cm^2 since the cathode was contaminated. However, since a cathode current convergence by a factor of 50 was obtained, optimism was expressed for the possibilities of high-density beam extraction by this method.

During the present report period tests were made on two tubes with separate ion and electron emitters, which gave considerably better results (highest current density was 32 amp/cm^2). A third tube, SE-4, has been built but not yet tested. In one of these tubes, designated SE-2, a niobium disk was used as an ionizing surface instead of graphite. Tubes SE-3 and SE-4 utilize a hafnium surface for cesium ionization and somewhat different geometries. The latter two were the first tubes built and tested under this Contract. (Tubes SE-1 and SE-2 were available from pre-Contract work). The test results, with some supplementary explanations of the theory of operation, are given in this Section. Observations of charge and potential state transitions and of oscillations are also described.

A. TESTS ON SEPARATE-EMITTER PLASMA TUBE SE-2

Tube SE-2 is similar to SE-1 which was described in Technical Note No. 2,[1] with the exception that SE-2 has a niobium ionizing surface. The heater shields for the ionizing disk were covered with an alundum coating to prevent cathode contamination. A schematic drawing of the tube is shown in Fig. 1. Note that this plasma gun has an ion-producing drift tube following the aperture.

A current density of 32 amp/cm^2 was extracted from the plasma. The plasma for this tube turned out to be of the common-emitter type instead of the duo-emitter type. This was due to a continuous deposition of L-cathode evaporants on the hot niobium surface. The ionization efficiency of niobium at 1000°C was found to be low so that high cesium pressure and niobium temperature were required. Due to the deposition of both L-cathode material and cesium at the hot niobium surface, that surface emitted both ions and electrons and was the prime source of the extracted current. A plot of extraction current vs. extractor potential with the niobium ionizing surface temperature as a parameter is shown in Fig. 2. At sufficiently low niobium temperatures most of the extracted current originates at the L-cathode whereas for higher temperatures most

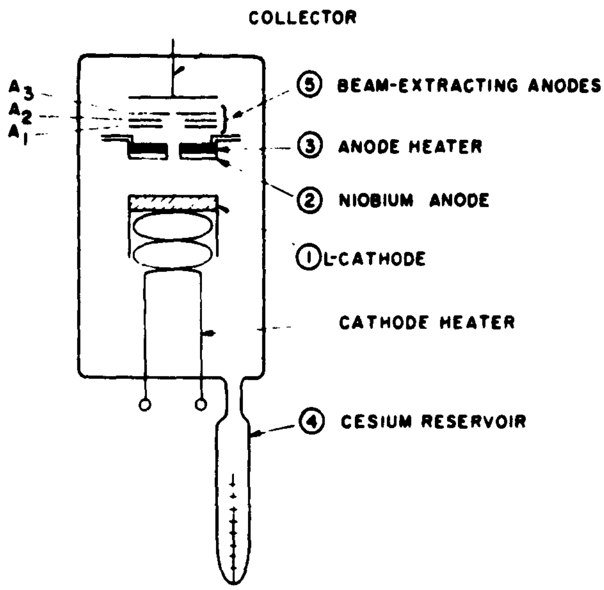


Fig. 1. Separate-emitter plasma gun SE-2.

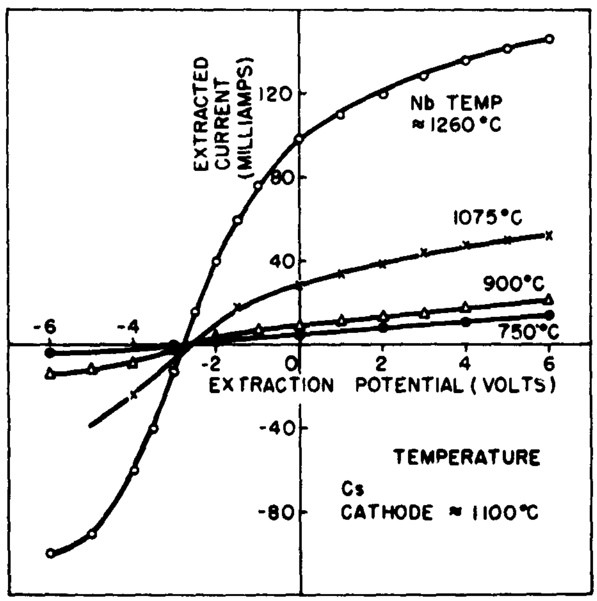


Fig. 2. Extracted current as a function of extractor potential for tube SE-2.

of the electrons originate from the niobium surface covered with L-cathode evaporants. The negative current obtained for sufficiently negative voltages represents ion current. At a bulb temperature of 150°C the cesium pressure was about 2×10^{18} cesium atoms/cm^2 sec. For 100% ionization efficiency this represents an ion current density of 1/3 amp/cm^2. Since the niobium disk is about 1/3 cm^2 in area, the ion current for 100% ionization would be about 100 ma. Thus from Fig. 2 we estimate that at 1260°C the niobium is a very efficient cesium ionizer. This high ion current provides an overabundance of ions.

The fact that the electron emission was produced by L-cathode material deposition on the heated niobium surface was verified by observing the electron current from the niobium as the L-cathode was cooled. The emission from niobium dropped as the L-cathode was cooled and increased again when the L-cathode was reheated. A similar effect was reported by Hernqvist and Johnson.[2]

Figure 3 shows the extracted current as a function of extraction potential with higher niobium temperatures and a cesium temperature of only 75°C. In this case the maximum extracted current density is about 11 amp/cm^2. The curve also shows that the ion current is considerably decreased because of the lowered cesium pressure and, therefore, lower ion generation rate.

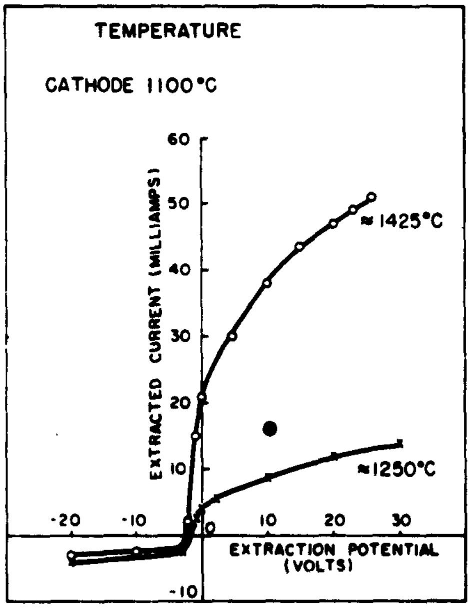


Fig. 3. Extracted current as a function of extractor potential for tube SE-2 at higher niobium temperatures.

B. SEPARATE-EMITTER PLASMA TUBE SE-3

A separate-emitter plasma tube (SE-3) utilizing a hafnium electrode for cesium ionization and an L-cathode for electron emission has been built (see Fig. 4) and tested. In this tube a duo-emitter-type plasma did form between the L-cathode and the hafnium ionizing electrode. Characteristics similar to those obtained for tube SE-1 (reported in Technical Note No. 2)[1] were obtained. The extracted current density from the plasma was, however, nearly an order of magnitude higher than previously reported.

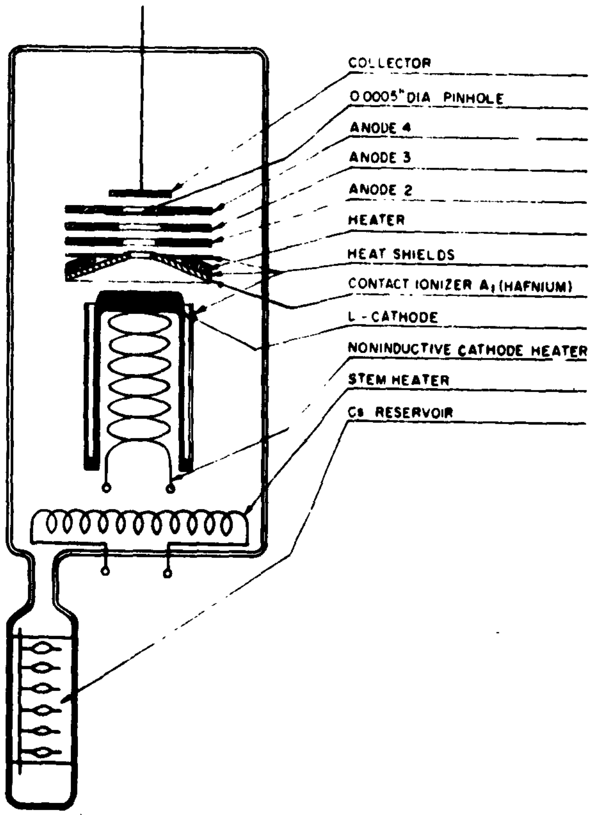


Fig. 4. Duo-emitter plasma gun SE-3.

Prior to a description of the results obtained with this tube it is instructive to review the Hernqvist-Fendley theory[3] of a duo-emitter diode of simplified geometry. They showed that an optimum plasma state can be reached between two surfaces one of which is ion emissive and the

other electron emissive. In their model (Fig. 5a) these surfaces are infinite parallel planes. Both ions and electrons are emitted with a Maxwellian velocity distribution.

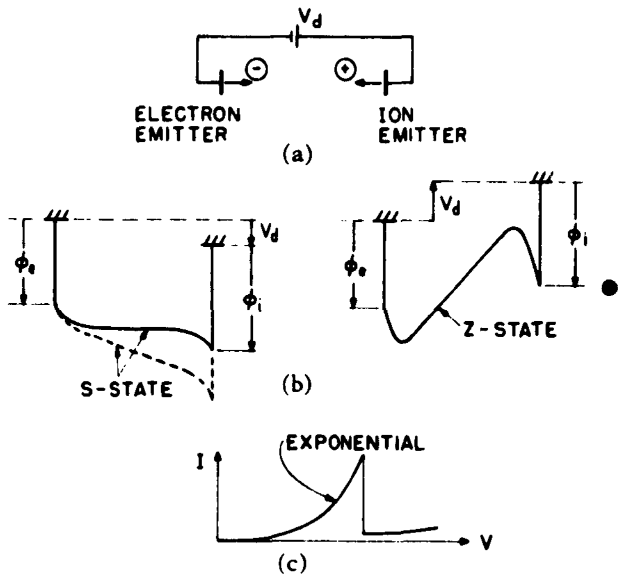


Fig. 5. Duo-emitter diode
(a) schematic,
(b) S- and Z-state potential distributions,
(c) I-V characteristic of diode.

For anode potentials lower than the optimum plasma state the electron current decreases exponentially with reduced voltage. This is characterized by the so-called "S-state" shown in Fig. 5b. For an anode potential higher than the one yielding an optimum plasma between emitters, an ion sheath forms in front of the ion emitter and an electron sheath in front of the electron emitter and a discontinuous transition into the so-called "Z-state" occurs (shown in Fig. 5b).

For the S-state shown in Fig. 5b the electron current flow from the electron to the ion emitter is given by

$$J_e = J_{es}\, exp \left(\frac{-q}{kT}\right) \left(\phi_i - \phi_e - V_d\right) \tag{1}$$

where

J_e is the electron current density in amps/cm^2,
J_{es} is the saturation electron current density of the electron emitter,
ϕ_i is the work function in volts of the ion emitter,
ϕ_e is the work function in volts of the electron emitter,
V_d is the external diode voltage as shown in Fig. 5a.

The maximum diode current was derived by Hernqvist and Fendley[3] from the following stability criteria:

$$\beta < [\exp \frac{q}{kT} (V_d - \phi_i + \phi_e)] \left[1 + Erf \sqrt{\frac{q}{kT} (V_d - \phi_i + \phi_e)} \right] \tag{2}$$

if $\beta > 1$

and

$$\beta > [\exp \frac{q}{kT} (V_d - \phi_i + \phi_e)] \left[1 + Erf \sqrt{\frac{q}{kT} (V_d - \phi_i + \phi_e)} \right] \tag{3}$$

if $\beta < 1$

where β is the absolute ratio of ion charge density at the ion emitter to the electron charge density at the cathode.

The diode current for the Z-state is low because of the retarding field sheath in front of each emitter. The theoretical diode characteristics are shown in Fig. 5c.

Provided that an S-state plasma is synthesized between the L-cathode and the hafnium ionizing electrode, the plasma can be made to effuse through the aperture of the ionizing electrode toward the extractor electrodes. Electrons can then be drawn from the S-state plasma edge by the accelerating electrodes. Two conditions must be met to extract a stable high density beam:

1. For an anchored plasma boundary the extracted current should not exceed the space-charge limited current determined by the potential of the accelerating electrode. For high current density operation a small spacing must be used between the accelerating electrode and the plasma edge.

2. The extracted current must not cause the current density through any part of the synthesized plasma diode region to exceed the values determined from Eqs. (1), (2) and (3).

In tube SE-3 no cesium recirculation was used; hence, high accelerating potentials could not be applied since gas breakdown would ensue. With sufficiently low potentials applied to the first extraction anode, the plasma which formed between the cathode and hafnium ionizer actually protruded through the aperture of the first extraction anode (Fig. 6a). The potential distribution possible with retarding and accelerating anode potentials are shown in Figs. 6b and 6c, respectively.

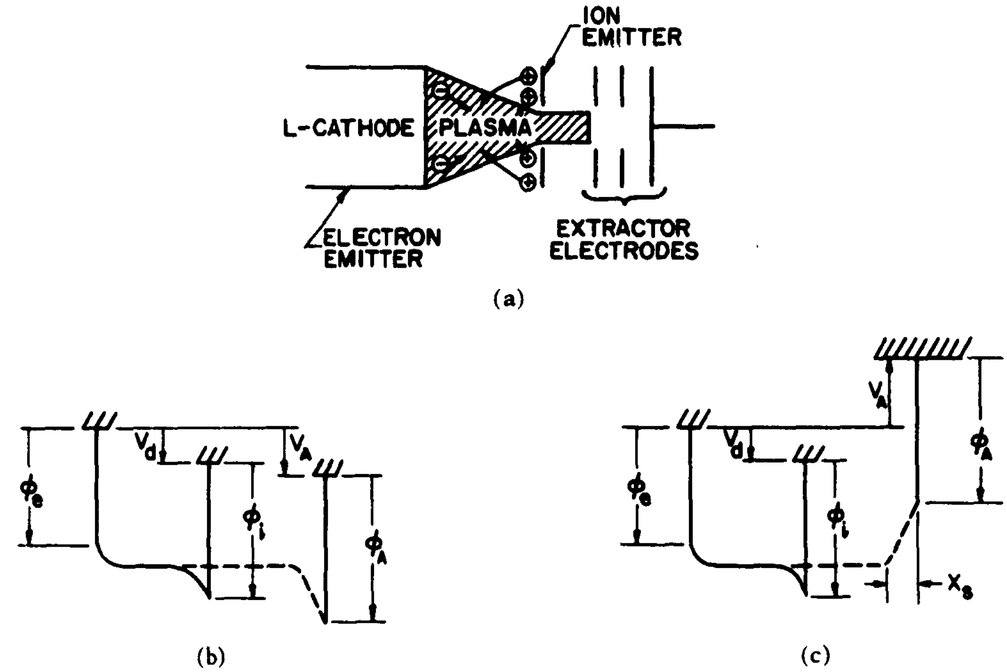


Fig. 6. Experimental model for electron extraction.

As the extracting anode potential V_A is raised, stable current flow may eventually become limited for any one of the following reasons:

- Condition 1 or 2 above is violated.
- As the extraction potential is raised the plasma edge moves back toward the electron exit aperture since ions are repelled.
- The plasma changes its potential profile or breaks up into a distribution with several maxima and minima.
- Voltage breakdown occurs.

The experimentally observed behavior is described below.

To obtain the diode characteristics of separate emitter tube SE-3 (shown schematically in Fig. 4) all collector electrodes were connected to the ion emitter. Thus the diode characteristic represents the electron current chiefly to the ionizing electrode. The I-V characteristics obtained are shown in Fig. 7. This characteristic follows the theoretical curve discussed in the previous

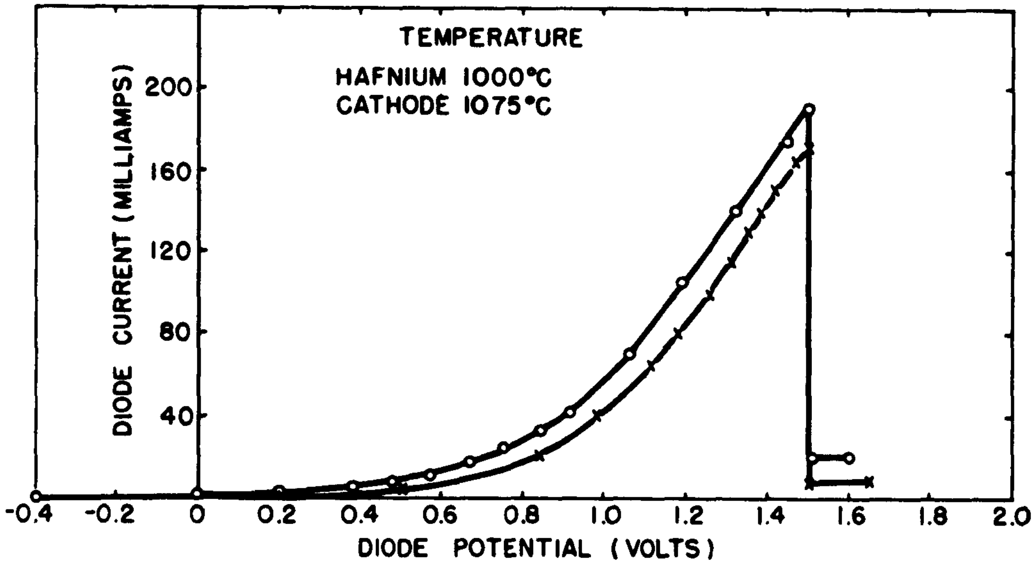


Fig. 7. Duo-emitter diode characteristic of tube SE-3.

section and clearly shows the existence of the high-current-flow and low-current-flow states. A semilogarithmic plot of the diode current as a function of external diode voltage (Fig. 8) shows that for most of the range of the S-state the current flow is exponential although a departure occurs at the highest currents. The electronic temperature determined from this semilog plot is about twice the cathode temperature.

The voltage at which the S-state becomes unstable corresponds to a difference of surface potential between emitters of

$$V_d - \phi_i + \phi_e = 1.4 - 3.78 + 2.2 = -0.18 \text{ volt} \tag{4}$$

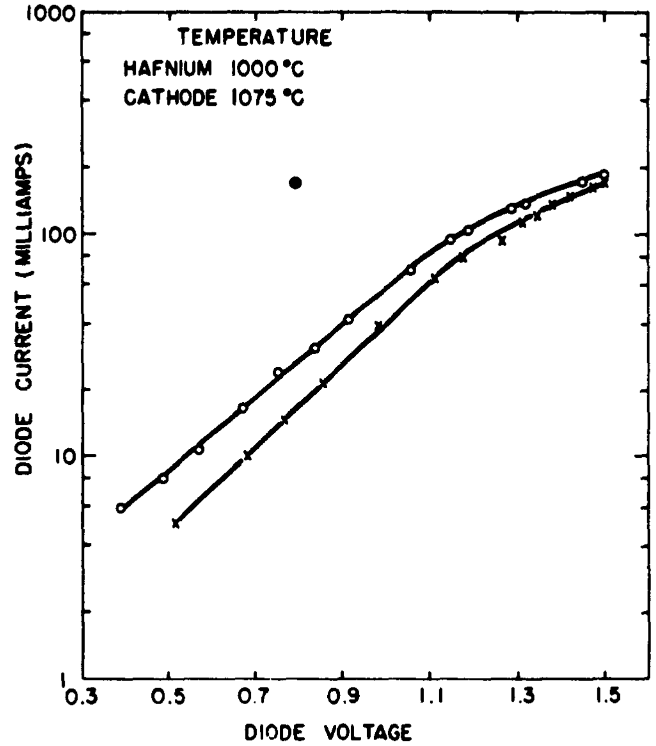


Fig. 8. Duo-emitter diode characteristics of tube SE-3 (semilog plot).

Using the results on stability obtained by Hernqvist and Fendley,[3] we find that the initial ion-to-electron charge density is

$$\beta \simeq 0.4 \tag{5}$$

The saturation current density of the L-cathode can be determined from Eq. (1). It is found to be about 1 amp/cm^2 which is low for an L-cathode.

Current was extracted from the diode region by applying a potential to the anodes following the electron exit aperture. A fairly dense plasma was required in the diode region to extract high current densities. Curves of extracted current as a function of the diode current (i.e., density of plasma) are shown in Figs. 9 and 10 for various values of extractor potential. The extracted current as a function of extractor voltage is plotted on semilog paper and 2/3-power paper in Figs. 11 through 14.

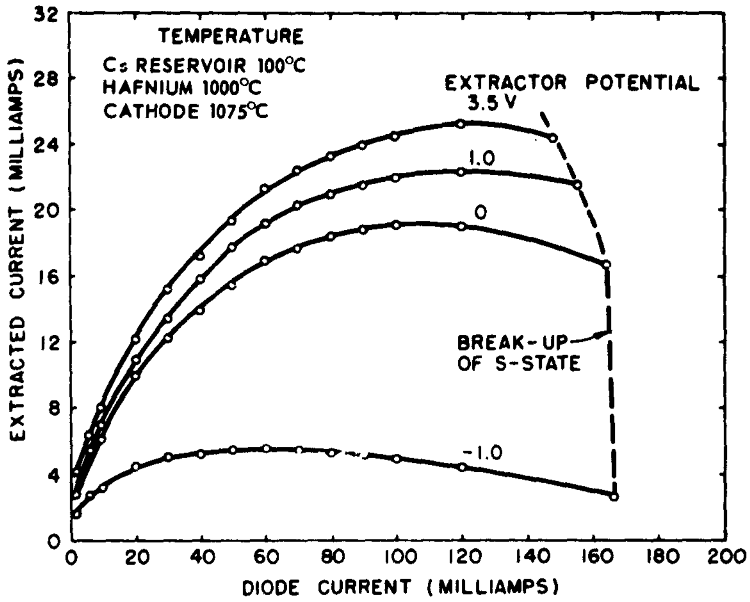


Fig. 9. Extracted current as a function of plasma density with extractor potential as parameter. Tube SE-3.

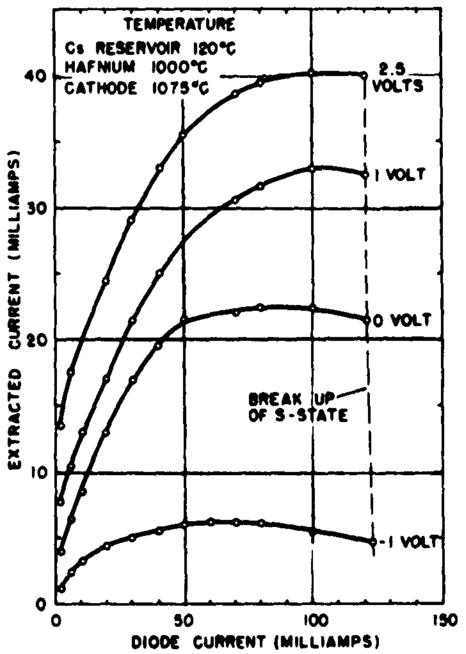


Fig. 10. Extracted current as a function of plasma density wi.h extractor potential as parameter. Tube SE-3.

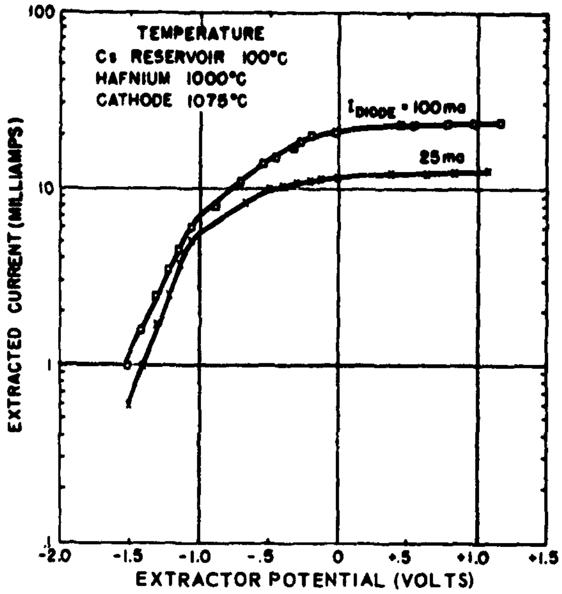


Fig. 11. Extracted current vs. extractor potential for SE-3 (semilog plot).

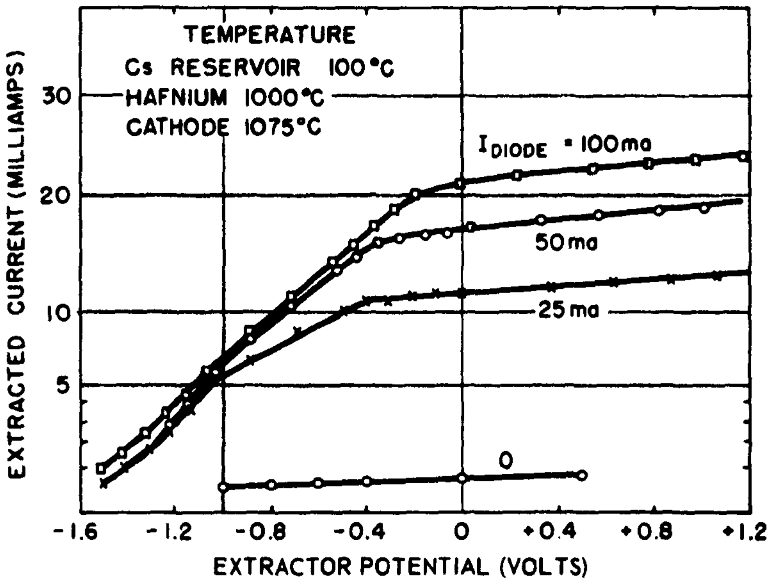


Fig. 12. Extracted current vs. extractor potential with diode current as a parameter for SE-3 (2/3-power plot).

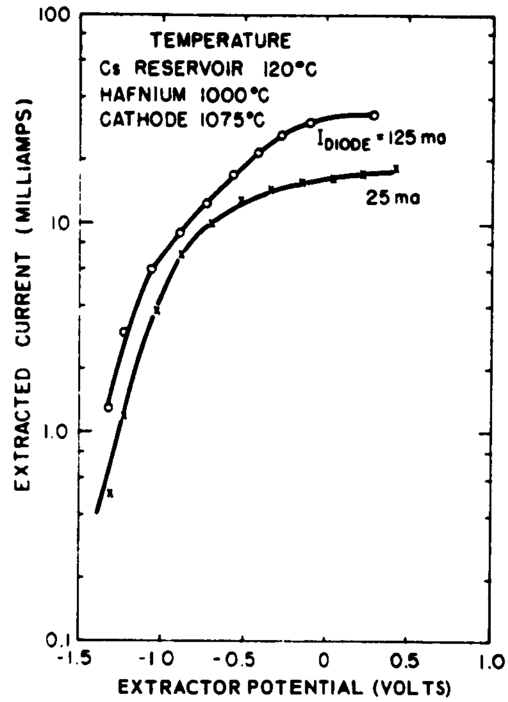


Fig. 13. Extracted current vs. extractor potential for tube SE-3 (semilog plot).

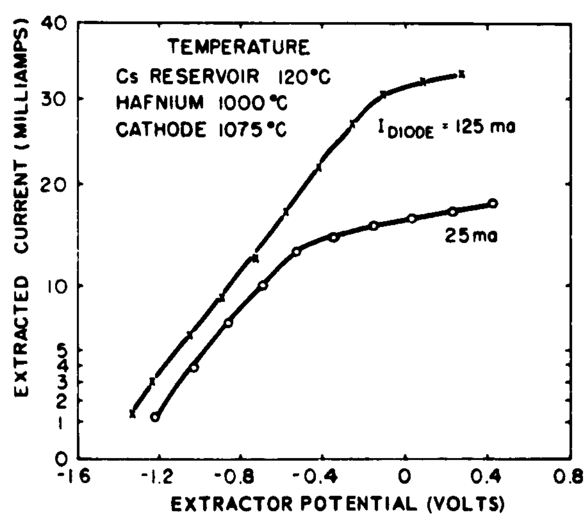


Fig. 14. Extracted current vs. extractor potential for tube SE-3 (2/3-power plot).

Figures 11-14 show that the extracted current is described by an exponential law for retarding collector potentials and a 3/2-power law for accelerating collector potentials. A third saturation-like region follows for sufficiently high accelerating potentials. It may be due to motion of the plasma edge, although this point has not yet been verified. The electrons flowing to the ionizing surface must overcome a sheath while there is no sheath for the extracted electrons. The extracted current density can therefore be somewhat higher than the diode current density without an accelerating extraction field. The experimentally observed current density without an extraction field was 40% higher than the diode current density. From the slope of the 3/2-power region of the I-V curves the distance between the plasma edge and the extracting anode can be found. A plot of this distance as a function of diode current is shown in Fig. 15.

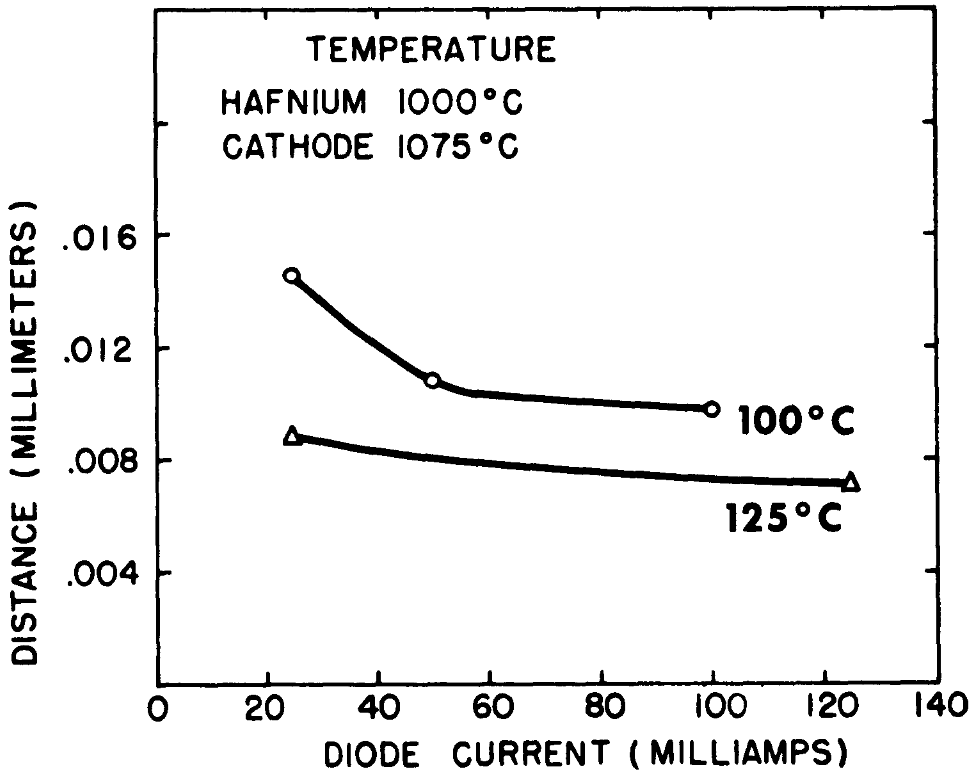


Fig. 15. Distance from plasma edge to accelerating extractor SE-3 (initial 3/2-power region) vs. diode current.

It is observed that this distance is of the order of a Debye length. The table below shows extracted currents obtained under various operating conditions:

TABLE I

MAXIMUM EXTRACTED CURRENTS (SE-3)

Diode Current – 150 ma, Diode Current Density – 0.45 amp/cm²

Cs TEMP. °C	CATH. TEMP. °C	HF. TEMP. °C	EXTRACTED CURRENT ma.	EXTRACTED CURRENT DENSITY amps/cm²
105	1100	1020	30	6.57
110	1087	1010	35	7.69
114	1075	1000	36	7.9
114	1087	1010	40	8.77
120	1087	1010	50	10.9
120	1120	1030	56	12.3

The table shows that extracted current densities of the order of 27 times the diode current density were obtained. Voltage breakdown prevented higher density operation. It is expected that plasma guns of the SE-3 type can give an order of magnitude higher current density if one uses:

- An uncontaminated L-cathode (emission density should be 5-10 amp/cm^2 instead of 1 amp/cm^2),
- Additional ionization in the exit-aperture area,
- Cesium recirculation to attain lower neutral Cs densities in the extraction region. This will permit higher extraction potentials to be used.

C. STABILITY OF THE DUO-EMITTER-TYPE PLASMA

With the duo-emitter plasma (i.e., S-state) between the L-cathode and the hafnium electrode, oscillations in the frequency range of several kilocycles to one megacycle were observed. The amplitude of these oscillations was only a few percent of the total current; they were of the type observed in energy converters.

The time for transition from a plasma S-state to a space-charge limited state was measured. The circuit used for the measurement is shown in Fig. 16a. A 60-cycle signal was applied to the circuit and the voltage across the diode was observed on an oscilloscope. A photograph of the current-voltage characteristic of the diode is shown in Fig. 17a. These characteristics are very

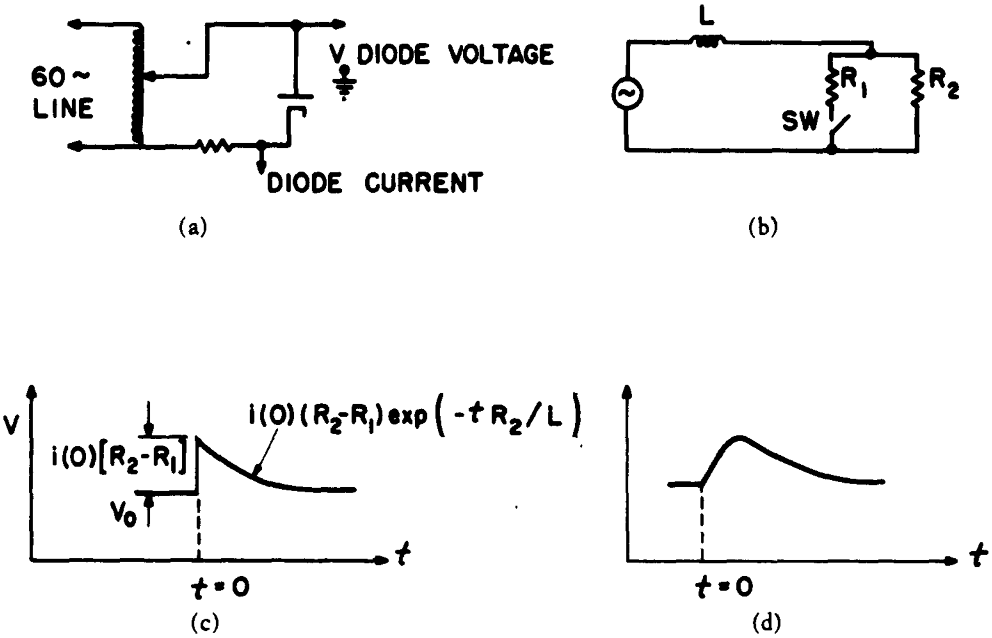


Fig. 16. Measurement of time for transition from S-state to Z-state (a) measurement circuit, (b) equivalent circuit, (c) voltage waveform with 0 switching time, (d) voltage waveform with finite switching time.

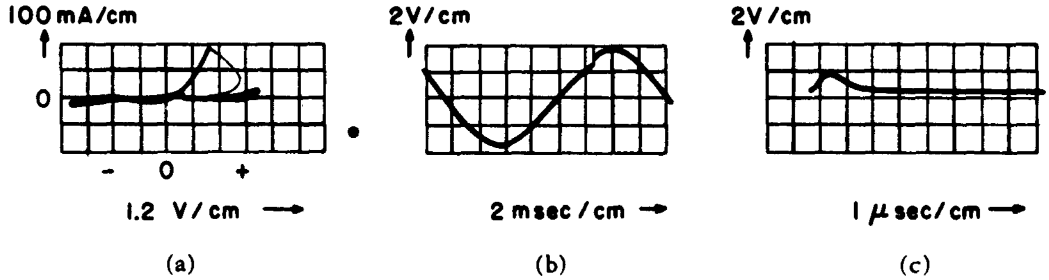


Fig. 17. Diode characteristics of SE-3, cathode temp. 1075°C, hafnium temp. 1000°C, Cs reservoir temp. 114°C.

similar to those determined by d-c measurements shown in Fig. 7. A photograph of the voltage across the diode as a function of time is shown for two time scales in Figs. 17b and 17c.

To interpret the above results one can consider the equivalent circuit shown in Fig. 16b. Here the resistor R_1 represents the ratio of diode voltage to current in the plasma state and R_2 the same ratio for a Z-state, i.e., space-charge limited state. Consideration of the switching from one to the other for an infinitely fast switch would give a current waveform as shown in Fig. 16c. Since the switching takes a finite time and there is some stray capacitance in the circuit the waveform will take the form shown in Fig. 16d. Correcting the measured rise-time to account for circuit response time gives a switchi-g time of 0.8 μsec. The switching time from a plasma state to a Z-state is determined by the time required to sweep the ions from the inter-electrode space. The sweeping is facilitated by an increase of the magnitude of the potential minimum in front of the cathode $|\Delta V_{min}|$ which is obtained from

$$J_{e\,Z\text{-}state}\Big|_{t=0^+} = J_{e\,S\text{-}state}\Big|_{t=0^-} \exp\left(\frac{-q|\Delta V_{min}|}{kT}\right) \tag{6}$$

One can obtain a rough measure of the ion transit time τ for an ion, in the center between the two electrodes $(x = d/2)$, assumed to move with a constant velocity $v_{ion} = \sqrt{\frac{2e}{M_i}|V_{min}|}$

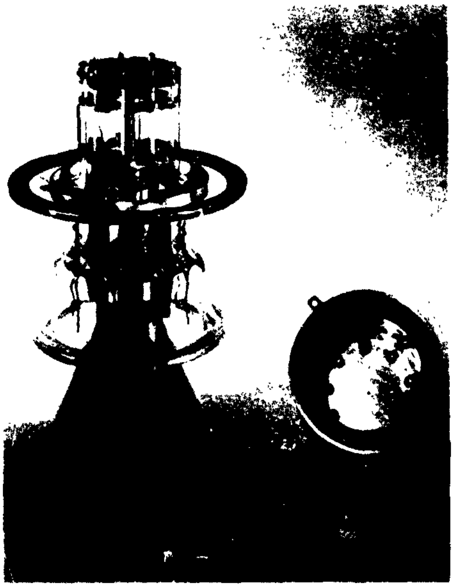
$$\tau = \frac{d/2}{\sqrt{2\frac{e}{M_i}|V_{min}|}}; \tag{7}$$

where d = interelectrode distance, M_i = ion mass. The ion transit time calculated on this basis is 0.935 μsec which compares well with the 0.8 μsec measured.

II. PLASMA CATHODE GUNS UTILIZING A COMMON SURFACE FOR ION AND ELECTRON EMISSION

The design of two plasma guns – CE-1 and CE-2 –, which utilize hollow cathodes for both contact ionization of cesium and thermionic electron emission was described in Technical Note No. 1.[4] The assembly and processing of tube CE-1 was completed during the third quarter and this tube is ready for testing. In addition to the features described in the Technical Note No. 1 this tube has a cesium recirculation system. This will enable several tests to be made with this tube, which were initially contemplated for the CE-2 tube. Several photographs were taken of the tube as the work progressed but prior to the addition of the cesium condenser and of the recirculation glassware. These photographs are shown in Figs. 18 to 21. As may be seen, the tube assembly proceeded on two separate tube sections, the lower and upper section. The two sections were sealed by means of a silver chloride seal at a temperature of about $475^{\circ}C$.

Figure 18a shows the cathode and electrode system and Fig. 18b shows the heat shields inside the magnetic shield. Figure 19 is a photograph of completed lower half of the tube. A mating upper half of the tube is depicted in Fig. 20. A platinum deposit coats the lip-area of the envelope halves illustrated in Figs. 19 and 20. This facilitates the silver chloride sealing of tubes.



(a) (b)

Fig. 18. Plasma cathode gun using a common surface for ion and electron emission.

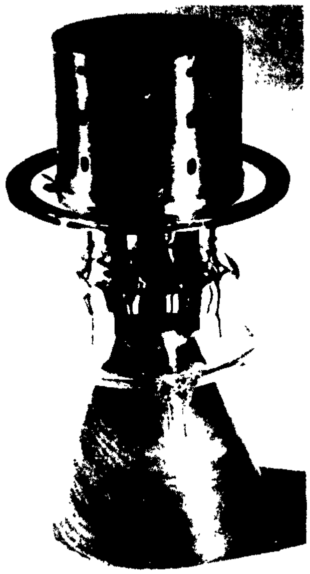


Fig. 19. Lower half of plasma cathode gun.

Fig. 20. Upper half of plasma cathode gun.

Fig. 21. Sealed plasma cathode gun.

Prior to sealing of the upper and lower tube sections the lower half of the tube containing the cathode and electrodes was tested for thermal and mechanical stability. The cathode was brought to full operating temperature (2250°K) in a belljar. The cathode was operated at that temperature for several hours and no difficulties in the mechanical or thermal aspects were encountered. Leakage paths which developed between several heat shield electrodes are not considered to be a serious problem since these electrodes will be operated at a very low potential.

Following the belljar tests the two halves of the tube were sealed at the lip-area of the envelope (Fig. 21). A silver chloride ring 0.100 in. wide and 0.025 in. thick was used as the sealing material. An oven was constructed to provide heating only over 6 inches of tube width in the vicinity of the lip-area. Argon gas was passed inside the tube to prevent the metal parts from oxidizing. The tube was subsequently exhaused at a pump station and baked for six hours at 375°C. The cathode was again brought to operating temperature on the exhaust station. A curve of cathode temperature as a function of cathode heater current is shown in Fig. 22. The heater current design value to bring the cathode to full operating temperature is shown in Fig. 22 to be only 10% lower than the required current.

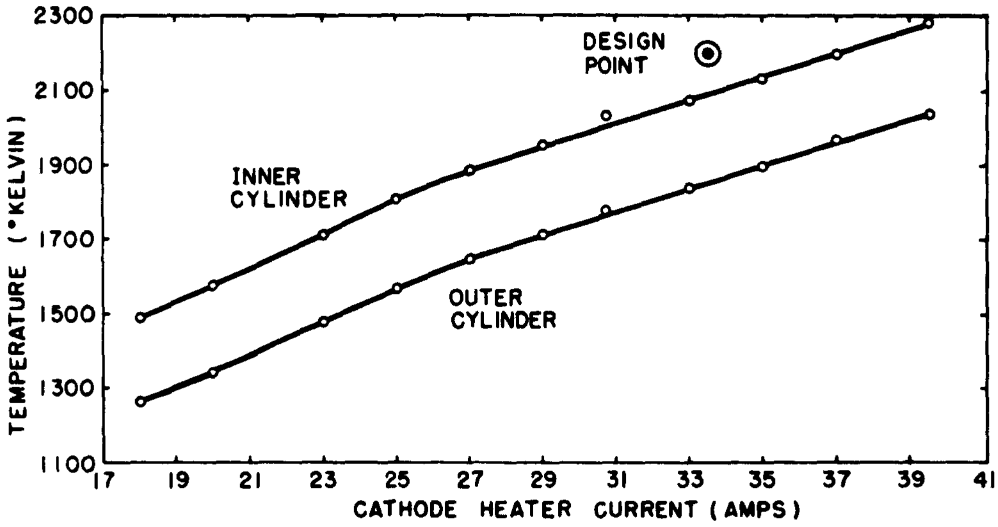


Fig. 22. Cathode temperature as a function of cathode heater current for CE-1.

Cesium was subsequently admitted into the tube and the tube was tipped off at a pressure of 10^{-7} mm Hg.

A test station for evaluating the tube is almost complete and tests will begin shortly. The final assembly of CE-2 will start after some results are obtained from CE-1.

III. SUMMARY OF TUBES INVESTIGATED TO DATE

A summary of the tubes investigated to date and of those uncompleted or contemplated is given below:

TUBE	TUBE TYPE	CATHODE MATERIAL Temp. °K	ION-EMITTER MATERIAL Temp. °K	CESIUM PRESSURE mm Hg	EXTRACTED CURRENT DENSITY amp/cm^2	REMARKS
High-Power Hollow Cathode	Common Emitter	Tantalum 2400	Tantalum 2400	10^{-2}	70	Total beam current 7 Amps.*
CE-1	Common Emitter	Tantalum 2250	Tantalum 2250	10^{-3}	Design Objective 100	Cathode satisfactory. Tube now being readied for extraction tests
CE-2	Common Emitter	"	"	10^{-3}	Design Objective 100	Intended for high-voltage studies. Tube is being assembled.
SE-1	Separate Emitter	L-Cathode 1490	Graphite 1373	3×10^{-4}	1.44	Contaminated L-Cathode
SE-2	Separate Emitter	L-Cathode 1400	Niobium 1533	10^{-2}	32	Operated unintentionally as a common-emitter tube
SE-3	Separate Emitter	L-Cathode 1400	Hafnium 1300	2×10^{-3}	12.3	L-Cathode contaminated and insufficient ions near exit aperture.
SE-4	Separate Emitter	L-Cathode	Hafnium			Tests incomplete.
SE-5	Separate Emitter				Objective 100	Being designed.

* The exit aperture for this tube had a 0.140 in. diameter. All other tubes in the list had 0.030 in. diameter apertures.

IV. PLANS FOR THE NEXT INTERVAL

Tests on common-emitter tube CE-1 will be carried out during the next Quarter. Tube CE-2 should also be completed within the next Quarter, at which time high-voltage beam studies will be initiated. The main effort is being concentrated on CE-1 and CE-2 since this type offers the best promise of yielding 100 amp/cm^2. However, the separate-emitter tubes operate at lower temperatures; they also are simpler to build. Hence, another tube, SE-5, incorporating the best features of the other SE tubes and having a separately biased drift tube following the exit aperture, is being designed. This tube is expected to yield higher density extracted beams. Theoretical studies of plasma stability and synthesis will be continued.

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1. A. L. Eichenbaum et al., Technical Note No. 2, Contract No. AF30(602)2767, 14 December 1962.

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4. A. L. Eichenbaum et al., Technical Note No. 1, Contract No. AF30(602)2767, September 14, 1962.

Rome Air Development Center, Griffiss AF Base, N. Y. Rpt. No. RADC-TDR-63-138. CESIUM VAPOR CATHODE STUDY. Tech. Note No. 3, March '63, 27 p. incl. illus., tables, and 4 ref.

Unclassified Report

Two approaches to the problem of extracting high-density electron beams from synthesized plasmas are under study. One uses a common surface for both ion and electron emission; the other employs separate surfaces.

The first tantalum common-emitter hollow cathode tube, CE-1, is to be tested. The cathode, designed to yield an extracted current density of 100 amp/cm^2, was heated to full operating temperature of 2250°K without mechanical or thermal difficulties.

Plasma-cathode tubes using separate ion and electron emitters can be operated at lower temperatures, and an extracted current density of 32 amp/cm2 was obtained from the aperture in a niobium electrode.

In another tube a hafnium surface was used for cesium contact ionization and a duo-emitter-type plasma was successfully synthesized. The extracted current density through the aperture was 12.3 amp/cm^2.

1. Cesium Electron Tubes
2. Electron Beams
3. Plasma Synthesis

I. AFSC Project 5573, Task 557303
II. Contract AF30(602)-2767
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